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Kultegin Aydin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Pennsylvania State University
University Park, PA 16802

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13. ABSTRACT (Maximum 200 words)

The primary objective of this research program was to investigate problems related to the use of a C-band polarimetric radar for estimating the rainfall in a region with complex terrain and where storm development and structure are highly variable and poorly understood. The anticipated experimental opportunities for conclusive testing of whether dual polarization C-band reflectivity factor measurements are adequate for quantitative estimation of rainfall under these conditions did not materialize. A number of associated problems were identified and subsequently investigated. Methods for reduction of clutter and noise in rainfall fields were developed. Techniques for translating radar-derived rainfall parameters to the ground were introduced. Storm runoff simulation studies were performed based on radar measurements in rainstorms. Tomographic imaging techniques, which use microwave propagation links, were studied for rainfall measurements in complex terrain. The effects of vertical reflectivity gradients and attenuation on radar measurements in rainfall were investigated and correction algorithms were tested for the latter. Attenuation in rainfall was observed as a major problem for C-band dual-polarization reflectivity factor measurements in rain. For operational purposes there are presently no demonstrated reliable attenuation correction methods. This indicates that S-band frequencies, which suffer little or negligible rainfall attenuation, should be the choice for operational rainfall measuring radars at this time.

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1.   STATEMENT OF THE PROBLEM STUDIED

The primary objective of this research program was to investigate problems related to the use of a C-band polarimetric radar for estimating the rainfall in a region with complex terrain and where storm development and structure are highly variable and poorly understood. The results are expected to advance the physical, meteorological interpretation of radar data and, consequently, contribute to an improved understanding of storm systems in the Arno river basin and their influence on hydrology, especially as they relate to flood development and its forecasting. Toward this end the Civil and Environmental Engineering Department at the Massachusetts Institute of Technology (MIT) were to use radar derived rain data and ground based rainrate and stream flow measurements to improve hydrological modeling and forecasting. The MIT effort was separately funded by ARO. This research, as well as the one at MIT, was conducted in collaboration with scientists in Italy.

2.   GENERAL CONCLUSIONS

This investigation focused on the potential utilization of employing the POLAR-55 C-band radar of the Italian Institute for Atmospheric Physics for monitoring rainfall in the region of Tuscany as part of an international cooperative program on flashflood forecasting in the Arno River Basin. The project contemplated that the radar would be fully operational shortly after the project began in September 1989. However, unforeseen technical problems arose with implementation of the radar's signal processing system and environmental (and scenic) considerations delayed approval of an appropriate radar site. These problems resulted in significant delays in the conduct of the planned experiments that were contemplated during the proposal phase of this project. Consequently, the project necessarily proceeded with investigations of a number of related problems. These included:

- the development of methodologies for radar-derived rainfall rate estimation in the presence of clutter and noise;

- translation of radar-derived volumetric rainfall parameters to the surface;

- storm runoff simulations to evaluate effects of naturally occurring spatial and temporal rainfall variations;

- tomographic imaging of rainfall fields as a basis for rainfall monitoring in complex terrain regions inaccessible to radar surveillance;

- investigation of vertical reflectivity gradients and their effects on radar measurements of rainfall resulting from range spreading;

• evaluations of C-band polarimetric parameters in rainfall through simulations based on raindrop size distribution measurements;

• development of PC-based computer codes for radar parameter computations for use in field operations and sensitivity studies; and

• development and application of algorithms for correction of reflectivity measurements affected by attenuation at C-band wavelengths.

This project, unfortunately, did not provide the anticipated experimental opportunities for conclusive testing of whether dual polarization C-band reflectivity factor measurements are adequate for quantitative estimation of rainfall in regions of complex terrain and when the measurements are affected by significant rainfall attenuation. Consequently, a number of associated problems, were identified and investigated via postulated simulations; these included range spreading and reflectivity gradient effects, the presence of ice contamination within the radar scattering volume, methods of identifying different hydrometeor phases, clutter contamination, detection and reduction, and C-band attenuation and reconstruction of reflectivity factor Z_H and differential reflectivity Z_{DR} radar parameters. Attenuation in rainfall was observed as a major problem for C-band dual-polarization reflectivity factor measurements in rain. For operational purposes there are presently no demonstrated reliable attenuation correction methods. This indicates that S-band frequencies, which suffer little or negligible rainfall attenuation, should be the choice for operational rainfall measuring radars at this time.

The results of this investigation demonstrated that the inherent problems associated with dual polarization radar estimation of rainfall appear tractable for research appllications. However, operational implementation of C-band radars for hydrological applications does not seem feasible at this time with only dual-polarization reflectivity factor measurements. Future studies should include not only measurements of (Z_H, Z_{DR}) but also specific differential phase K_{DP}, linear depolarization ratio LDR and polarimetric correlation parameters. The additional information provided by these parameters are considered useful for resolving some of the above-identified problems that can affect rainfall estimation by radar. Furthermore, modern radar technology can readily generate all these parameters.

The following sections outline results of the various investigations conducted under this contract. Detailed information on each may be found in the referenced publications.

3.   SUMMARY OF THE MOST IMPORTANT RESULTS
     3.1   Clutter and Noise Reduction in Rainfall Fields

Several methods of clutter and noise reduction from dual-polarization radar estimates of rainfall fields were investigated (David, 1989).   Measurements of Z_H and Z_{DR} were first filtered by discarding values that fell outside bounds expected for rainfall. These bounds were based on inferences made from computations of the radar parameters derived from disdrometer measurements and analytical forms of raindrop size distributions.   In addition to removing ice-phase data points, this procedure successfully identified significant amounts of clutter present in actual radar data.   After removing (Z_H, Z_{DR}) pairs of data points outside the expected rainfall bounds, rainfall rates were computed and smoothed by employing one of three different spatial filters. These included a 9-point median filter, a 9-point max/median filter and a 25-point max/median filter.   Application of these filters to the raw data yielded excessive smoothing compared to when clutter data points identified in accordance with the aforementioned procedure were removed prior to spatial filtering. Among the filters, the 9-point median filter produced the greatest smoothing while both max/median filters produced approximately the same degree of smoothing.

Three clutter identification schemes, two of which were based on difference fields of rainfall rates and the third on difference fields of Z_{DR}, were examined.

1.   Points in the R difference field greater than twice the expected standard deviation of R in known rainfall.
2.   Points in the R difference field whose values lie in the seventh or greater highest values out of those in a 9-point window, centered on the points considered.
3.   Points in the Z_{DR} difference field greater than twice the expected standard deviation of Z_{DR} in known rainfall.

Note that Schemes 1 and 3 utilized a priori information on the spatial variability of R and Z_{DR} in rainfall, respectively.   The data used to establish these conditions were derived from radar measurements obtained during a storm in Colorado.   Although each scheme produced similarly good results, more extensive radar measurements of rainfall in different storm environments are desirable in order to establish better estimates of the spatial variability of R and Z_{DR} in rain.   Note that the Scheme 2 performed similarly even though it did not utilize any a priori information about the variability of the rainfall rate field; this is important since it can more readily be implemented in hardware, potentially resulting in a great reduction in processing time of radar data.   The performance of the clutter identification and filtering schemes were illustrated with data from S-band radar measurements because the C-band radar data were not available at the time of this research.

Multiple-parameter radar data classification schemes were also developed for discrimination of rainfall from ground clutter (Giuli et al., 1991).   Combined tests on dual-polarization radar

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observables (Z_H, Z_{DR}), Doppler velocity, and area clutter maps were utilized for this purpose. The classification schemes rely heavily on the rainfall discrimination capability of Z_H and Z_{DR}. The spatial variability of Z_{DR} appears to be very promising for ground clutter versus rain discrimination. Preliminary studies, using actual radar measurements, produced very encouraging results. The assessment of the proposed schemes requires considerably more research focusing on different rainfall conditions and in situ verification. Potential applications include real-time processing of radar data for estimating the spatial distribution of rainfall rates for weather and hydrological nowcasting purposes in clutter affected regions.

3.2 Translation of Radar-Derived Rainfall Parameters to the Ground

In order to translate radar-derived rainfall parameters to the ground, a cross-correlation technique was employed to determine the velocity of storms and regions within storms (Lure, 1990). This procedure also yielded information on the correlation lengths of storms. Rainfall events from MAYPOLE '84 (MAY POLarization Experiments, designed to assess the utility of multiparameter radar measurements for observations of rain and hailstorms) in Colorado and MIST '86 (MIcroburst Severe Thunderstorm experiment) in Alabama were used to illustrate the technique. Rainfall rate R and median volume diameter D_o were computed from (Z_H, Z_{DR}) after identification and removal of regions suspected of containing hail. An image restoration procedure was then used to fill in the area suspected of being contaminated by hail and/or clutter. This was followed by an image enhancement technique, using the Hanning filter, that resulted in reduced statistical fluctuations and retention of actual spatial variations of the data. The effects of window size were studied; this resulted in a determination of optimal window sizes for each storm. The cross-correlation technique consisted of cross-correlating the reflectivity fields in two dimensions from successive volume scans, performed around three minutes apart. The results were very similar with estimates obtained visually from computer-generated color graphic displays of the same data fields. Variability of the correlation lengths of Z_H, R and D_o, corresponding to different times during the MAYPOLE and MIST rainfall events, were found. Generally, the correlation lengths of R were less than those of Z_H and D_o. Furthermore, it was shown that the spatial variability of the shape and concentration factors of raindrop size distributions could be inferred from the correlation lengths of Z_H and D_o. A detailed translation study of rainfall was performed with the MIST data set, since it exhibited finer spatial variability and larger vertical depth of the rainfall field. The translation of the Z_H, R and D_o fields from 4.5 km down to 0.9 km MSL followed a consistent pattern which clearly illustrated the value of the technique for inferring ground-based rainfall estimates from radar measurements aloft.

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This methodology was applied to S-band radar measurements in Colorado for comparison with ground-based raingage measurements at separate sites (Aydin et al., 1990). The results indicate that the differential reflectivity technique performed consistently well at both sites, whereas the Z-R relationships performed well at one site and not as well at the other. The biases and standard errors for the combination of the measurements at both sites were +11% (overestimated by radar) and 38% for R_{ZDR} (estimated using Z_H and Z_{DR}), -13% (underestimated by radar) and 45% for R_{MP} (estimated from the Marshall-Palmer Z-R relation).

3.3 Storm Runoff Simulation

In this study the feasibility of processing dual-polarization radar-derived image of storm rainfall rates into runoff hydrographs was examined (Seliga et al., 1991). The radar data were obtained from an event in Colorado using NCAR CP-2 dual-polarization (Z_H, Z_{DR}) S-band radar measurements. The runoff simulation was applied to the watershed of the Greve river which is a major tributary of the Arno river and located around 20 kilometers south of Florence. The main purpose of the investigation concentrated on determining the sensitivity of the simulated watershed response to the spatial and temporal distributions and resolutions of rainfall, the direction of storm cell movement and the extent of watershed subdivision. Major findings of the study indicate that hydrograph response is greatly affected by the rainfall rate spatial resolution available for analysis, that a spatial model cell size of around 5 km^2 appears sufficient for hydrograph generation and that hydrograph response of a watershed of this size (around 60 km^2) and shape (10x6 km) is relatively insensitive to the direction of storm motion.

3.4 Tomographic Imaging of Rainfall Fields

Tomographic reconstruction algorithms have been prevalently used in the medical imaging field wherein a series of one-dimensional measurements or projections are transformed into a two-dimensional cross sectional image. The potential high resolution attained using these methods, coupled with their non-invasive nature, have made tomographic imaging attractive to widely diverse applications such as geophysical imaging, non-destructive testing in industrial manufacturing , and mostly, imaging ground-level rain intensities (Giuli et al., 1991). Repeated over time, tomographic imaging of rainfall can monitor both spatial and temporal characteristics as rain events develop. For certain applications, this method possesses a significant advantage over current methods which use either raingages or weather radar, as it allows the observation of rain events in real-time (or near real-time) with relatively high resolution over a reasonably large area (e.g., 500 km^2). The original work by Giuli et al., (1991) proved the feasibility of implementing

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tomographic imaging of rainfall fields using one-way specific
attenuation measurements over a small fixed network. However,
the use of specific attenuation measurements alone for
tomographic reconstruction is not without limitation. Besides
affirming the original techniques developed by Giuli et al., this
research explored the following issues: 1) transmitter and
receiver siting as it affects accumulated and instantaneous image
formation; 2) introduction of multi-parameter propagation
observables (such as specific differential phase shift and
specific differential attenuation) and their role in practical
system implementation; 3) basis function selection in deference
to physical storm characteristics; and 4) the ability of the
tomographic imaging process to adapt to different types and
intensities of storms (Yim et al., 1992).

Five different storms were used to evaluated the tomographic
rainfield imaging technique, including: 1) an intense rain event;
2) baseline (used in previous studies), 3) storm with faster
decay time and slower generation of new cells, 4) storm with
changing directions, and 5) light, stratiform rain. Overall, the
tomographic imaging method was able to identify the main
underlying structure of the rain events, with better results as
integration time increases. The results of these storm images
are documented in Yim (1991).

3.5 Vertical Reflectivity Gradients
The effects of beam-spreading on radar measurements of radar
reflectivity factor and differential reflectivity were modelled
and examined (Czapski et al., 1991). This is important for
understanding the limitations of radar measurements that, due to
blocking by complex terrain or the presence of low-level melting,
may necessarily include a distribution of scatter from rainfall,
melting hydrometeors and various ice-phase hydrometeors. It was
concluded that $1°$ beam data at long range from the radar must be
treated with care both within the outside the melting layer.
These effects and resulting limitations on the estimation of
rainfall rates under such conditions require the development of
algorithms to account for such effects.

3.6 C-Band Radar Parameters in Rainfall
A simulation study of C-band polarimetric radar observables
for rain was conducted using disdrometer measurements of drop
size distribution (DSDs) and gamma model DSDs (Aydin and
Giridhar, 1992). It was shown that rainfall data are clustered
in specific regions of the $Z_H - Z_{DR}$, $Z_H - K_{DP}$, $Z_H - Z_{DP}$, and $\rho - Z_{DR}$
planes, where Z_H, Z_{DR}, K_{DP}, Z_{DP}, and ρ correspond to the effective
reflectivity factor at horizontal polarization, differential
reflectivity, specific differential phase, difference
reflectivity and cross-correlation coefficient between H and V
polarized radar returns, respectively. It is proposed that data
points lying outside these regions can be interpreted as
hydrometeors other than pure rain, such as hail, graupel, snow

and mixed phase precipitation. Relationships between specific attenuation A_H (as well as specific differential attenuation ΔA_{HV}) and specific differential phase shift K_{DP} were derived for estimating attenuation in rainfall in order to recover the values of Z_H and Z_{DR} measurements at C-band which have experienced attenuation. Relationships between rainfall rate R and K_{DP}, R and (Z_H, Z_{DR}), and R and Z_H were also derived and evaluated. The R-(Z_H, Z_{DR}) relationship provided the best estimates, closely followed the R - K_{DP} relationship. The R - Z_H relationships did not perform as well as the other two. The effects of raindrop temperature between 0°C to 20°C and raindrop canting (Gaussian canting angle distribution with 10° standard derivation and 0° mean value; 0° corresponds to symmetry axis along vertical direction) on the radar estimates of R and A using Z_H, Z_{DR} and K_{DP} were investigated. It was found that both temperature and canting had little effect on the estimates of R from R - Z_H, R - (Z_H, Z_{DR}) and R - K_{DP} relations relative to the 10°C relations. Canting caused less than 7% error relative to the no canting relations. On the other hand, the estimates of specific attenuation (A_H and A_V) and specific differential attenuation (ΔA_{HV}) from A_H - K_{DP}, A_V - K_{DP}, and ΔA_{HV} - K_{DP} relations were shown to be significantly affected by raindrop temperature from 0°C to 20°C leading to errors ranging from 14% to 26% relative to the 10°C relations. Canting caused less than 8% error. The backscattering differential phase shift δ and the correlation coefficient ρ_{HV} were also seen to be significantly affected by raindrop temperature.

3.7 PC-Based Computer Code for Radar Parameters
A computer code was developed that computes radar polarimetric parameters for use in field applications and related studies of their dependence on hydrometeor characteristics (Czapski et al., 1993). The code models different hydrometeor types, including raindrops, hail, graupel, and two other types of ice and mixed-phase particles. For each hydrometeor type, the user can specify a variety of parameters (e.g., equivolume diameter, axial ratio, density, canting angle, etc.) as well as several shapes and size distributions. The software calculates both monostatic radar parameters and propagation effects. Available parameters include: reflectivity factors at H and V polarizations (Z_H, Z_V), differential reflectivity Z_{DR}, circular depolarization ratio CDR, linear depolarization ratio LDR and specific differential attenuation ΔA and phase shift K_{DP}, all at K- X-, C- and S-band wavelengths. The code is fully interactive and easy to upgrade by creating new data bases for other types of hydrometeor models. It is user-friendly and intended primarily as a tool for use during polarimetric radar field experiments.

3.8 Polarimetric Radar Observations in Severe Storms
Dual-polarization radar measurements were made simultaneously with particle probes on the T-28 aircraft as it penetrated through a hailstorm in central Oklahoma on June 5,

1991 (Aydin et al., 1993). This experiment was conducted as part of the Cooperative Oklahoma Profilers Studies (COPS'91) at the National Severe Storms Laboratory (NSSL). Reflectivity factor (Z_H) and differential reflectivity (Z_{DR}) measurements were used for detecting hail and graupel, which were confirmed in situ with aircraft. Simulations of these radar measurements were derived from T-28 aircraft-based measurements of hydrometeor size and shape using a foil impactor and a 2D-P probe. The simulated Z_H and Z_{DR} compared well with the actual radar measurements along the aircraft track.

Two other studies were conducted with data from NSSL's polarimetric radar (Zrnic et al., 1993a, b). These focused on using polarimetric radar measurements for discriminating between hydrometeor types and quantification of mixed phase hydrometeors. The radar parameters, used for this purpose were Z_H, Z_{DR}, K_{DP}, ρ and δ (see Section 2.5 for the corresponding terminology). Both studies demonstrated the complementary nature of these parameters. Heavy rainshafts were clearly identified from significant K_{DP} values. Aircraft observations and a one-dimensional cloud model were used to explain some polarimetric measurements and to infer the presence of aggregates, graupel, and supercooled cloud water in the stratiform region.

3.9 C-Band Radar Measurements and Attenuation Correction

Preliminary analysis of actual radar data from Italy, which became available to us for the first time in March of 1993, has confirmed our concerns about the significant effects of attenuation due to rain on dual polarization radar reflectivity measurements at C-band. These effects are most readily observable on differential reflectivity (Z_{DR}) data along radials with long rain paths. Z_{DR} gradually decreases due to differential attenuation, from positive values (as expected in rain) to negative values at the furtherest gates. These effects are not obvious from the reflectivity factor (Z_H) profiles, even though Z_H is also reduced along the ray by attenuation due to rain. An attenuation correction scheme using Z_H and Z_{DR} (Aydin et al., 1989) was applied to predict attenuation and correct the radar observables at each range gate. This technique is quite sensitive to biases in both Z_H and Z_{DR} resulting from calibration errors. Furthermore, ground clutter entering through the sidelobes may be affecting the data, which in turn will be causing errors in the attenuation correction process. It appears that the use of a complementary correction scheme such as the specific differential phase shift (K_{DP}) technique (Aydin and Giridhar, 1992) would help by providing a consistency check between the two methods. Further measurements are needed to better understand the strengths and limitations of these techniques.

4. LIST OF PUBLICATIONS
   4.1 <u>Journal Publications</u>

Aydin, K., Y. Zhao, and T.A. Seliga, "A Differential Reflectivity Radar Technique for Measuring Hail: Observations During the Denver Hailstorm of June 13, 1984," <u>Journal of Atmospheric and Oceanic Technology</u>, vol. <u>7</u>, pp. 104-113, 1990.

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Czapski, P. and T.A. Seliga, "A PC-Based Simulation Code for Radar Polarimetric Field Applications in Meteorology," Proceedings, 1993 International Geoscience and Remote Sensing Symposium (IGARSS'93), Tokyo, Japan, 303-305, August 1993.

4.3 Ph.D. Theses

Zhao, Y., "Polarimetric Radar Remote Sensing of Hailstones," Ph.D. Dissertation, The Pennsylvania State University, Department of Electrical Engineering, December 1989.

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4.4 M.S. Theses

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5. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

    ### 5.1 Senior Personnel

    K. Aydin (Principal Investigator, Penn State University)

    T.A. Seliga (Subcontracting Investigator, Note: Dr. T.A. Seliga and Dr. K. Aydin were initially Co-PIs on this contract. Dr. Seliga moved to the University of Washington in April of 1990 and continued collaboration from there under a

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subcontract.)
                    G. Aron (Faculty Associate, Penn State University)

        5.2   Graduate Students
                    Y. Zhao (Ph.D. Degree: 1989, Penn State University)
                    T. David (M.S. Degree: 1989, Penn State University)
                    Y.M. Lure (Ph.D. Degree: 1990, Penn State University)
                    S. Yim (M.S. Degree: 1991, University of Washington)
                    C. Tang (Penn State University)
                    D. Engelson (University of Washington)
                    V. Giridhar (M.S. Degree: 1992, Penn State University)
                    P. Czapski (M.S. Degree: 1992, University of
                        Washington)
                    M. Northrop (M.S.Degree: 1993, University of
                        Washington)
                    M. Machulsky (Penn State University)
                    G. Wang (University of Washington)
                    A. Graylin (Undergraduate student at the University of
                        Washington)

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